



RESEARCH ARTICLE

Effect of microbial enrichment on nutrient dynamics and microbial population of different organic composts

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Abstract

The increasing demand for sustainable agricultural practices has emphasised the importance of organic nutrient sources for maintaining soil health and productivity. Organic manures and composts play a vital role in improving soil physical, chemical and biological properties while supplying essential plant nutrients. However, the nutrient availability from organic composts largely depends on their degree of decomposition, carbon-to-nutrient ratios and microbial activity during composting. This study evaluated the effect of microbial enrichment on nutrient composition, microbial population and maturity indices of different organic composts. Four composts, namely urban compost (UC), press mud compost (PMC), poultry manure (PM) and vermicompost (VC), were subjected to enrichment using a microbial consortium along with a biocontrol agent during October 2023 at the Research Farm, Department of Soil Science, Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri, Maharashtra, India. The composts were inoculated with a bacterial consortia and *Trichoderma* spp. at 0.2 % (w/w) and incubated for 30 days under controlled moisture conditions. Samples were collected at 15 and 30 days to assess physico-chemical, nutrient and biological properties. Results indicated a gradual reduction in pH, electrical conductivity, total organic carbon, C : N ratio and C : P ratio during enrichment, reflecting accelerated decomposition and compost stabilisation. Significant increases in total nitrogen, phosphorus, potassium and microbial population were observed at 30 days of enrichment. Paired *t*-test analysis confirmed statistically significant improvement in nutrient content across all composts after enrichment. Among the composts, PM and VC exhibited superior nutrient enrichment and microbial activity. The study concludes that microbial enrichment effectively enhances compost quality and promotes the production of nutrient-rich organic amendments suitable for sustainable agriculture.

Keywords: carbon : nitrogen ratio; carbon : phosphorous ratio; compost enrichment; microbial consortium; nutrient mineralisation

Introduction

In semi-arid regions of India, cereal-based cropping systems such as wheat–maize are facing challenges of soil degradation and fertility decline due to excessive use of chemical fertilisers, which necessitates the adoption of sustainable nutrient management approaches organic composts such as urban compost (UC), press mud compost (PMC), poultry manure (PM) and vermicompost (VC) serve as important sources of organic matter and essential plant nutrients, contributing to improved soil physical, chemical and biological properties (1). However, the effectiveness of these organic inputs largely depends on their degree of decomposition, nutrient composition and microbial activity. Moreover, organic manures generally contain relatively low concentrations of readily available nutrients, which may not fully meet crop nutrient requirements when used alone (2).

In recent years, global food security has faced increasing pressure due to rapid population growth and the continuous decline in arable land (3, 4). The necessity of meeting food demands for a growing population has intensified agricultural production, leading

to widespread and often excessive use of chemical fertilisers (5). Although chemical inputs have significantly enhanced crop yields, their indiscriminate use has resulted in adverse environmental and health consequences (6, 7).

In this context, biofertilisers and microbially enriched organic amendments have emerged as sustainable alternatives within integrated nutrient management systems (8, 9). Biofertilisers consist of beneficial microorganisms capable of colonising the rhizosphere or plant tissues when applied to soil or seeds (10, 11). These microorganisms enhance nutrient availability through biological nitrogen (N) fixation, solubilisation of phosphorus (P) and potassium (K), mobilisation of micronutrients and production of plant growth-promoting substances (12). By promoting nutrient recycling through natural biological processes, they improve soil fertility and agricultural sustainability (13).

With increasing agricultural production, the generation of agricultural residues and organic wastes has also risen substantially (14). Composting these residues offers an effective waste management strategy while producing valuable soil amendments. The quality of compost, including its carbon (C) to– N ratio (C : N),

macro and micronutrient content and overall maturity, is strongly influenced by the nature of the feedstock and the composting process (15). Therefore, microbial enrichment using beneficial consortia and biocontrol agents presents a promising approach to accelerate compost stabilisation, enhance nutrient mineralisation and improve compost quality.

In this context, the present study was undertaken to evaluate the effect of microbial enrichment on nutrient dynamics, microbial population dynamics and compost maturity indices across different organic compost types.

Materials and Methods

Compost enrichment

A compost enrichment experiment was conducted during October 2023 at the Research Farm, Post Graduate Institute, Department of Soil Science, Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri. The site is geographically located at 19°20'33.2" N latitude and 74°38'51.1" E longitude, with an elevation of 513 m above mean sea level, situated on the eastern side of the Western Ghats in Maharashtra. The climate of the region is semi-arid tropical steppe climate, characterised by hot dry summers and cool winters and the area falls under the scarcity zone. Four commonly used composts, namely UC, PMM, PM and VC, were selected for microbial enrichment.

Experimental details of compost enrichment

A compost enrichment experiment was conducted in October 2023 to evaluate changes in nutrient composition and microbial populations during the microbial enrichment of different organic composts. The experiment was conducted with single replication for each compost type. Four organic composts, namely UC, PMM, PM and VC, were selected for the study due to their widespread use in agricultural production systems. The enrichment process involved inoculation with beneficial microbial cultures to enhance the nutrient content and microbial activity of the composts.

Microbial inoculants used for compost enrichment

Compost enrichment was carried out using a bacterial consortium combined with a biocontrol agent (*Trichoderma* spp.), applied at a rate of 0.2% (w/w) to each compost.

The selected strains act synergistically: *Azotobacter chroococcum* for biological nitrogen fixation,

Bacillus polymyxa and *Pseudomonas striata* as phosphate-solubilising bacteria (PSB) and *Bacillus* spp. and *Pseudomonas fluorescens* as potassium-solubilising bacteria (KSB). and *Trichoderma* spp. provides biocontrol benefits. This consortium enhances nutrient availability, microbial persistence and compost maturity during enrichment.

All bacterial strains *Azotobacter*, PSB and KSB were originally isolated from healthy and native agricultural soils and maintained at the from the Biofertiliser Production Unit, Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri. The viable cell counts of the inoculants were: *Azotobacter* 1×10^{10} CFU/mL, PSB – 1×10^8 CFU/mL and KSB – 1×10^8 CFU/mL. These are standardised, laboratory-maintained biofertiliser strains, also produced for commercial distribution. *Azotobacter* is a free-living nitrogen-fixing bacterium, PSB facilitates solubilisation of insoluble phosphates and KSB enhances the availability of K through mineral solubilisation.

Enrichment process

A total of 25 kg samples of each compost type were weighed and inoculated with the microbial consortium at 0.2 % (w/w). A required quantity of 25 kg of each compost was taken separately and inoculated with the microbial consortium at 0.2 % (w/w). The experiment was conducted with single replication for each compost type and no formal experimental design was adopted.

The inoculated composts were incubated for 30 days in gunny bags, maintaining a moisture content of approximately 60 % (w/w) throughout the incubation period. Moisture content was maintained on a weight-by-weight (w/w) basis ($\approx 60\%$) by periodic addition of water based on weight loss, ensuring uniform moisture throughout the incubation period. Temperature during incubation was maintained at room temperature (25–30 °C) under laboratory conditions throughout the study.

Compost samples were collected at 15 and 30 days of incubation after thorough mixing for subsequent analysis. The samples were air-dried under shade, ground gently, passed through a 2 mm sieve and stored in clean, airtight containers at room temperature for physicochemical analysis. For microbial analysis, fresh samples were stored in a refrigerator (4 °C) until further use.

Observations recorded

The following observations were recorded during the experiment:

I. Initial characterisation of uninoculated composts

Initial characterisation of the uninoculated composts was carried out prior to enrichment.

II. Analysis during enrichment (15 and 30 days)

Compost samples collected at 15 and 30 days were analysed for physico-chemical and biological properties. Compost enrichment was conducted for 30 days on pre-mature composts (UC, PM, VC and PMM) that had completed the primary composting phase. The pH and electrical conductivity of the composts were determined in a 1 : 10 compost-water suspension using potentiometric and conductometric methods, respectively, as described by Jackson (16). Total carbon content was estimated by the dry ashing method (17), while total nitrogen was determined using the micro-Kjeldahl method (17). Total phosphorus was analysed by the vanadomolybdate yellow colorimetric method and total K was estimated using a flame photometer (18). The C : N ratio was calculated from the values of total carbon and total N.

Micronutrient concentrations, including zinc (Zn), manganese (Mn), copper (Cu) and iron (Fe), as well as heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr) and nickel (Ni), were determined using atomic absorption spectrophotometry after appropriate digestion of compost samples, following the method described by Zasoski (19). The biological properties of the composts were assessed by estimating the total microbial population, including bacteria, fungi and actinomycetes, using the serial dilution and plate count method. Different culture media were used for the enumeration of each microbial group, namely Nutrient Agar for bacteria, Rose Bengal Agar for fungi and Kenknight's medium for actinomycetes. Compost samples were serially diluted using sterile distilled water and appropriate dilutions were plated on respective media by using the pour plate technique. The inoculated plates were incubated at 28–30 °C for 3–7 days under sterile conditions. After incubation, colonies were counted and the microbial population was expressed as colony forming units per gram of compost (CFU g⁻¹).

as per the standard procedure (20).

Carbon: nitrogen ratio

The C : N ratio was calculated by dividing the total organic C content (%) by the total nitrogen content (%) of the compost.

$$\text{C : N ratio} = \frac{\text{Total organic carbon}}{\text{Total nitrogen}} \quad (\text{Eq. 1})$$

Carbon: phosphorus ratio

The C:P ratio was calculated by dividing the total organic carbon content (%) by the total phosphorus content (%) of the compost.

$$\text{C : P ratio} = \frac{\text{Total organic carbon}}{\text{Total phosphorus}} \quad (\text{Eq. 2})$$

The percentage carbon loss was calculated to determine the extent of organic C mineralisation during compost enrichment. It was computed by subtracting the final total organic C (TOC) from the initial TOC, dividing the difference by the initial TOC and multiplying by 100. A higher percentage indicates greater carbon mineralisation and compost stabilisation.

$$\text{Total organic carbon loss (\%)} = \frac{\text{Initial TOC} - \text{Final TOC}}{\text{Initial TOC}} \times 100 \quad (\text{Eq. 3})$$

Statistical analysis

Statistical analysis was carried out using Microsoft Excel. The data obtained before and after 30 days of microbial enrichment of composts with single replication was compared using paired *t*-test to evaluate significant changes in nutrient content and microbial population. The level of significance was set at $p \leq 0.05$. The study focused on evaluating changes within the same compost samples before and after enrichment; hence, paired *t*-test was applied for dependent observations. Due to single replication, ANOVA and Post-hoc test were not appropriate as it requires replication to estimate error variance. No formal statistical design (e.g., CRD) was applied.

Results

Characterisation of organic manures

The initial characterisation of organic manures showed considerable variation in physico-chemical, nutrient and biological properties among compost sources (Table 1). The pH of all manures ranged from neutral to slightly alkaline (7.09–7.90). Electrical conductivity ranged from 2.01 to 2.71 dS m⁻¹, with PM showing the highest value, while press mud compost and vermicompost showed moderate electrical conductivity (EC) levels. Total organic C content 24.25 % in press mud compost. The C : N ratio varied widely, with PM (8.59) and VC (10.63) exhibiting lower ratios. Poultry manure contained the highest concentrations of major nutrients (N, P and K), followed by VC. Micronutrient concentrations were adequate and within permissible limits across all manures, while Heavy metals in the composts were quantified (Table 1). The concentrations of Pd, Cd, Cr and Ni were below the permissible limits for agricultural use (Pb ≤ 50 mg kg⁻¹, Cd ≤ 3 mg kg⁻¹, Cr ≤ 100 mg kg⁻¹, Ni ≤ 50 mg kg⁻¹) (21). Urban compost recorded higher levels of Pb (9.50 mg kg⁻¹) and Ni (5.00 mg kg⁻¹) relative to other composts, though still below safe limits. This may partially explain the comparatively lower microbial populations and nutrient mineralisation observed in UC. Poultry manure and VC remained nutrient-rich and biologically active, with lower C : N ratios and higher microbial counts, supporting their superior performance as organic inputs. Poultry manure recorded the highest populations of bacteria, fungi and actinomycetes, followed by VC. Overall, PM and VC emerged as nutrient-rich and biologically active organic inputs compared to farmyard manure (FYM) and UC (1).

Periodical changes in nutrient content of compost during enrichment

Between 15 and 30 days of inoculation, all composts showed improved stabilisation and maturity (Table 2). The pH remained nearly stable, while EC and organic C decreased, indicating ongoing decomposition. The C : N and C : P ratios decreased and ash content increased due to mineralisation. Total N, P and K contents increased at 30 days, with PM and VC showing higher nutrient enrichment. Microbial populations (bacteria, fungi and actinomycetes) increased markedly after 15 days, indicating enhanced biological activity and compost quality. During the 30-day enrichment period, distinct variations were observed among different composts with respect to

Table 1. Characterisation of organic manures

Sl. No.	Properties of manures	UC	PMC	PM	VC
1.	pH (1:10)	7.90	7.80	7.70	7.16
2.	EC (dS m ⁻¹) (1:10)	2.01	2.20	2.71	2.50
3.	Moisture (%)	34.05	37.55	38.60	34.85
4.	Ash (%)	67.40	58.20	60.00	67.00
5.	Total N (%)	1.30	1.40	2.70	1.80
6.	Total P (%)	0.70	1.20	2.10	1.10
7.	Total K (%)	0.80	0.90	1.60	1.50
8.	Total Fe (mg kg ⁻¹)	1740	1400	1500	1650
9.	Total Mn (mg kg ⁻¹)	425	375	360	400
10.	Total Zn (mg kg ⁻¹)	140	139	145	150
11.	Total Cu (mg kg ⁻¹)	111	100	101	110
12.	Pb (mg kg ⁻¹)	9.50	-	-	-
13.	Cd (mg kg ⁻¹)	2.70	0.03	0.76	0.02
14.	Cr (mg kg ⁻¹)	3.90	1.13	0.02	0.02
15.	Ni (mg kg ⁻¹)	5.00	2.40	1.20	1.20
16.	Fungi (CFU x10 ⁴ g ⁻¹)	7	9	13	11
17.	Actinomycetes (CFUx10 ⁵ g ⁻¹)	11	12	20	17
18.	Bacteria (CFU x10 ⁶ g ⁻¹)	25	29	37	34

UC: urban compost; PMC: press mud compost; PM: poultry manure; VC: vermicompost; EC: electrical conductivity; N: nitrogen; P: phosphorus; K: potassium; Fe: iron; Mn: manganese; Zn: zinc; Cu: copper; Pb: lead; Cd: cadmium; Cr: chromium; Ni: nickel; CFU: colony-forming units.

Table 2. Periodical changes in nutrient content of compost during enrichment

Sl. No.	Properties of compost	At 15 days				At 30 days			
		UC	PMC	PM	VC	UC	PMC	PM	VC
1.	pH (1:10)	7.80	7.70	7.60	7.14	7.77	7.65	7.58	7.13
2.	EC (dS m ⁻¹) (1:10)	2.00	2.70	2.19	2.48	1.19	2.60	2.17	2.45
3.	Moisture (%)	60.15	61.55	60.60	60.75	60.45	60.40	61.05	61.30
4.	Ash (%)	69.40	59.80	61.60	69.00	70.40	60.40	63.60	70.80
5.	Total N (%)	1.50	1.80	2.90	2.10	1.70	2.00	3.10	2.40
6.	Total P (%)	0.90	1.50	2.20	1.40	1.10	1.70	2.30	1.60
7.	Total K (%)	1.00	1.10	1.70	1.70	1.20	1.30	1.80	1.80
8.	Total Fe (mg kg ⁻¹)	1765	1420	1560	1686	1770	1455	1585	1695
9.	Total Mn (mg kg ⁻¹)	429	380	371	408	436	390	382	415
10.	Total Zn (mg kg ⁻¹)	144	140	147	154	149	143	151	157
11.	Total Cu (mg kg ⁻¹)	120	105	110	120	127	110	126	125
12.	Pb (mg kg ⁻¹)	9.00	-	-	-	8.50	-	-	-
13.	Cd (mg kg ⁻¹)	2.20	0.02	0.01	0.01	1.90	0.02	0.01	0.01
14.	Cr (mg kg ⁻¹)	3.40	1.00	0.50	-	3.00	0.70	0.20	-
15.	Ni (mg kg ⁻¹)	4.50	2.10	0.54	0.98	3.90	1.80	0.32	0.50
16.	Fungi (CFU×10 ⁴ g ⁻¹)	9	12	18	16	12	17	21	19
17.	Actinomycetes (CFU×10 ⁵ g ⁻¹)	14	16	23	19	18	20	29	24
18.	Bacteria (CFU×10 ⁶ g ⁻¹)	32	38	47	42	46	49	58	54

UC: urban compost; PMC: press mud compost; PM: poultry manure; VC: vermicompost; EC: electrical conductivity; N: nitrogen; P: phosphorus; K: potassium; Fe: iron; Mn: manganese; Zn: zinc; Cu: copper; Pb: lead; Cd: cadmium; Cr: chromium; Ni: nickel; CFU: colony-forming units.

nutrient content, C: N ratio and microbial population. Poultry manure exhibited the most pronounced improvement, showing the highest increase in N, P and K contents (2.90 to 3.10 %, 2.20 to 2.30 % and 1.70 to 1.80 %, respectively) along with the sharpest decline in C : N ratio (7.68 to 6.81). It also supported the maximum microbial population, particularly bacteria (47 to 58 CFU×10⁶ g⁻¹), fungi (18 to 21 CFU×10⁴ g⁻¹) and actinomycetes (23 to 29 CFU×10⁵ g⁻¹), indicating rapid mineralisation and superior compost quality. Vermicompost ranked next, with consistent improvement in NPK (2.1 to 2.4 %, 1.4 to 1.6 % and 1.7 to 1.8 %), reduction in C: N ratio (8.56 to 7.06) and high microbial activity (bacteria: 42 to 54 CFU×10⁶ g⁻¹; fungi: 16 to 19 CFU×10⁴ g⁻¹; actinomycetes 19 to 24 CFU×10⁵ g⁻¹). Press mud compost recorded moderate enrichment in nutrients (N: 1.8 to 2.0 %, P: 1.5 to 1.7 %, K: 1.1 to 1.3 %) and microbial growth (bacteria: 38 to 49 CFU×10⁶ g⁻¹, fungi: 12 to 17 CFU×10⁴ g⁻¹, actinomycetes 16 to 20 CFU×10⁵ g⁻¹), with a reduction in C : N ratio from 12.95 to 11.48. Urban compost, though showing slight increases in NPK (1.5 to 1.7 %, 0.9 to 1.1 % and 1.0 to 1.2 %) and microbial population (bacteria: 32 to 46 CFU×10⁶ g⁻¹, fungi: 9 to 12 CFU×10⁴ g⁻¹, 14 to 18 actinomycetes CFU×10⁵ g⁻¹), accumulated relatively higher levels of heavy metals such as Pb, Cd, Cr and Ni compared to other composts, making it the least effective. Overall, the performance order of composts during enrichment was: PM>VC>PMM>UC.

Heat map of compost analysis at 15 and 30 days after enrichment

The heat map of compost analysis at 15 and 30 days after enrichment revealed a marked improvement in nutrient content and microbial population with composting duration. At 30 days, all compost types showed higher total N, P and K compared to 15 days, with PM recorded the highest values (N: 3.10 %, P: 2.30 %, K: 1.80 %), as depicted in Fig. 1. Micronutrients such as Fe, Mn, Zn and Cu also exhibited slight increases or stabilisation over time. Microbial populations, including fungi, actinomycetes and bacteria, increased significantly by 30 days, particularly in PM (fungi: 21 ×10⁴ CFU g⁻¹, actinomycetes: 29×10⁵ CFU g⁻¹, bacteria: 58×10⁶ CFU g⁻¹).

Paired t-test of nutrient content during enrichment

The detailed statistical comparison is presented in Table 3. The parameters analysed included total N, P, K, micronutrients (Fe, Mn, Zn and Cu) and microbial populations such as fungi, actinomycetes and bacteria. A paired t-test was conducted to compare the nutrient content of UC at the initial stage and after 30 days of microbial enrichment. The analysis showed a statistically significant increase in nutrient levels after enrichment ($t = 3.22, p < 0.05$). The very high Pearson correlation ($r = 0.9999$) between paired observations reflects strong consistency in the measured changes across all replicates. Pearson correlation analysis was performed to assess the consistency of changes between paired observations. The high correlation ($r = 0.9999$) indicates consistent trends between initial and enriched samples. Given that this study involved single-replication data, the correlation reflects trend consistency rather than independent variability.

The comparative statistical details are presented in Table 4. A paired t-test was performed to evaluate changes in the nutrient content of press mud compost before and after 30 days of microbial enrichment. The results showed a statistically significant improvement ($t = 2.34, p = 0.0437$). The high Pearson correlation ($r = 0.9999$) indicates strong consistency in the observed differences across all replicates.

Details of the paired analysis are outlined in Table 5. A paired t-test was conducted to assess the change in nutrient content of PM before and after 30 days of microbial enrichment. The analysis revealed a statistically significant improvement in nutrient levels ($t = 2.28, p = 0.048$). The strong Pearson correlation ($r = 0.9999$) between paired observations demonstrates high consistency in the measured differences across replicates.

A summary of the statistical comparison is presented in Table 6. A paired t-test was performed to evaluate changes in the nutrient content of vermicompost before and after 30 days of microbial enrichment. The results indicated a statistically significant improvement ($t = 2.77, p = 0.0215$). The very high Pearson correlation ($r = 0.9999$) reflects strong consistency in the observed differences across all replicates.

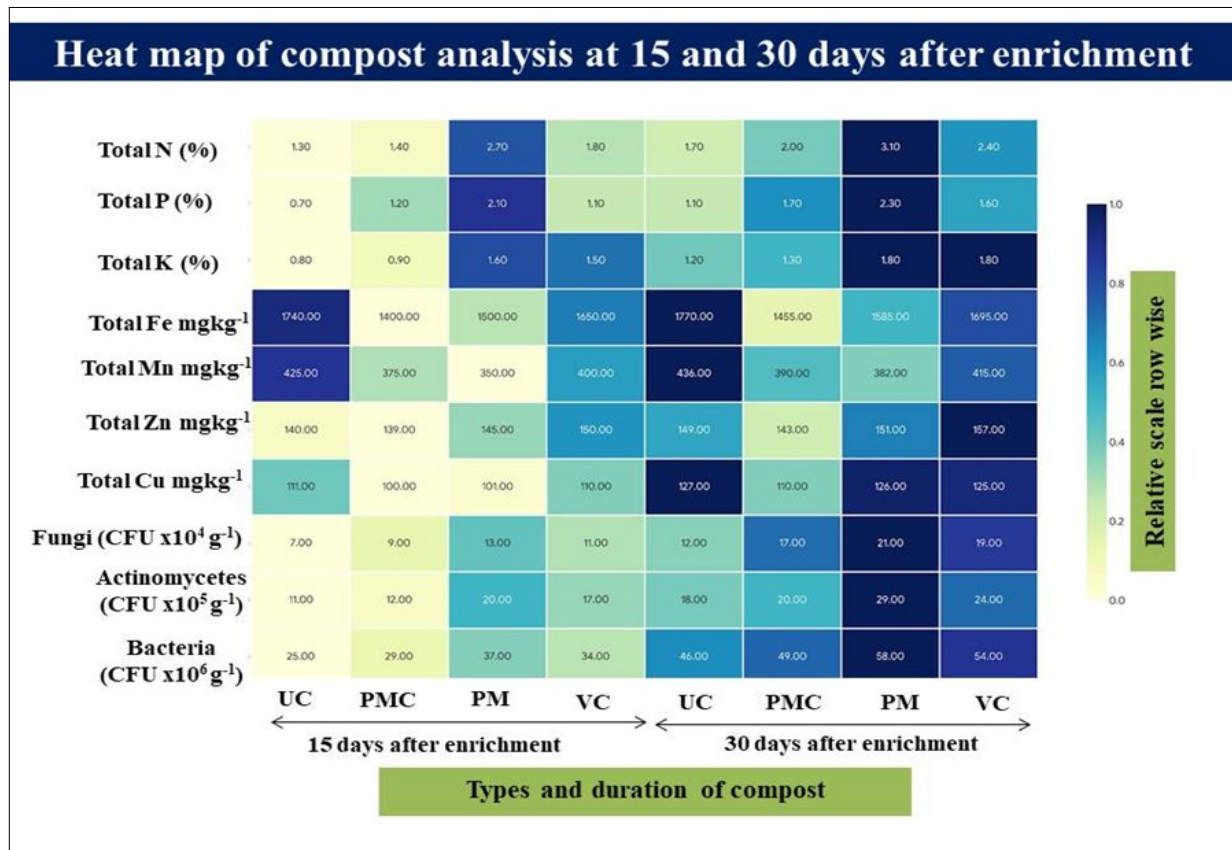


Fig. 1. Heat map of compost analysis at 15 and 30 days after enrichment.

Table 3. Paired *t*- Test analysis of nutrient content of urban compost: initial vs. after enrichment (30 days)

t-Test: paired two sample for means		
	UC after 30 days enrichment	Initial UC
Mean	256.2	246.18
Variance	300836.8	292766.4
Observations	10	10
Pearson correlation	0.99993	
Hypothesised mean Difference	0	
df	9	
<i>t</i> Stat	3.223741	
P(T ≤ <i>t</i>) one-tail	0.005213	
<i>t</i> Critical one-tail	1.833113	
P(T ≤ <i>t</i>) two-tail	0.010427	
<i>t</i> Critical two-tail	2.262157	

UC: urban compost.

Table 5. Paired *t*- test analysis of nutrient content of poultry manure: initial vs. after enrichment (30 days)

t-Test: paired two sample for means		
	PM after 30 days enrichment	Initial PM
Mean	235.92	217.24
Variance	238323.1	214860.7
Observations	10	10
Pearson correlation	0.999868	
Hypothesised mean difference	0	
df	9	
<i>t</i> Stat	2.286525	
P(T ≤ <i>t</i>) one-tail	0.024023	
<i>t</i> Critical one-tail	1.833113	
P(T ≤ <i>t</i>) two-tail	0.048047	
<i>t</i> Critical two-tail	2.262157	

PM: poultry manure

Table 4. Paired *t*- test analysis of nutrient content of press mud compost: initial vs. after enrichment (30 days)

t-Test: paired two sample for means		
	PMC after 30 days enrichment	Initial PMC
Mean	218.9	206.75
Variance	202844.5	189284.5
Observations	10	10
Pearson correlation	0.999913	
Hypothesised mean difference	0	
df	9	
<i>t</i> Stat	2.343799	
P(T ≤ <i>t</i>) one-tail	0.021874	
<i>t</i> Critical one-tail	1.833113	
P(T ≤ <i>t</i>) two-tail	0.043747	
<i>t</i> Critical two-tail	2.262157	

PMC: press mud compost.

Table 6. Paired *t*- Test analysis of nutrient content of vermicompost: initial vs. after enrichment (30 days)

t-Test: paired two sample for means		
	VC after 30 days enrichment	Initial VC
Mean	249.48	237.64
Variance	274109.5	261549.4
Observations	10	10
Pearson correlation	0.999936	
Hypothesised mean difference	0	
df	9	
<i>t</i> Stat	2.777167	
P(T ≤ <i>t</i>) one-tail	0.01075	
<i>t</i> Critical one-tail	1.833113	
P(T ≤ <i>t</i>) two-tail	0.0215	
<i>t</i> Critical two-tail	2.262157	

VC: vermicompost

C : N ratio

The periodical changes in the C : N ratio of different composts over 30 days of enrichment revealed significant variation in decomposition and nutrient stabilisation (Fig. 2). All composts showed a declining trend in C : N ratio, indicating ongoing carbon mineralisation and enhanced microbial activity. The PM exhibited the lowest initial C : N ratio (8.59) and decreased further to 6.81 by 30 days, reflecting rapid decomposition and greater nutrient mineralisation potential. Vermicompost also showed a notable decline from 10.63 to 7.06, indicating efficient microbial processing. In contrast, UC and PMC started with higher C : N ratios (14.55 and 17.32, respectively) and decreased more gradually to 10.10 and 11.48, respectively, suggesting slower organic matter turnover. Overall, the faster reduction in C:N ratio in PM and VC indicates higher microbial activity and rapid stabilisation, whereas UC and PMC require longer enrichment periods to achieve comparable maturity.

C : P ratio

The temporal changes in the C:P ratio of different compost types (UC, PMC, PM and VC) over 30 days are presented in Fig. 3. At the beginning, the C : P ratio was highest in UC (27.1), followed by PMC (20.2), VC (17.4) and PM (11.1). This indicates that the initial C content relative to phosphorus was highest in UC and lowest in PM, reflecting the differences in raw material composition. During enrichment, all treatments exhibited a declining trend in C : P ratio, indicating progressive decomposition of organic C and stabilisation of compost. By Day 15, significant reductions were observed in UC (19.7), PMC (15.5), VC (12.8) and PM (10.1), reflecting microbial mineralisation of carbon and the relative enrichment of P. The decline continued up to day 30, with UC showing the highest C : P ratio (15.6) and PM the lowest (9.2). This trend suggests that composting promoted carbon loss through microbial respiration while phosphorus remained relatively stable, leading to a decrease in the C : P ratio. PM and VC exhibited lower initial C : P ratios and smaller reductions over time, suggesting rapid decomposition and early stabilisation.

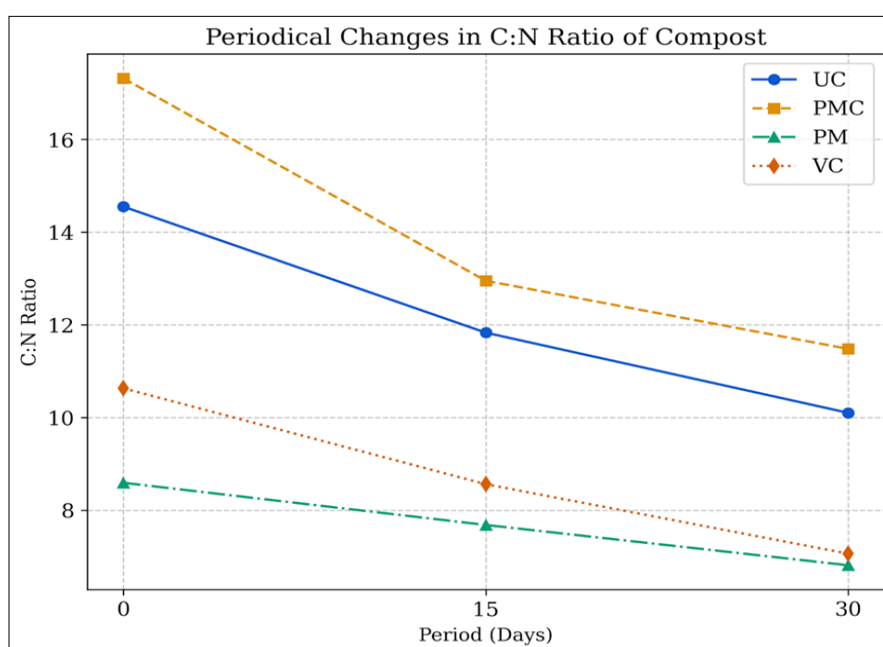


Fig. 2. Periodical changes in the C:N ratio of composts.

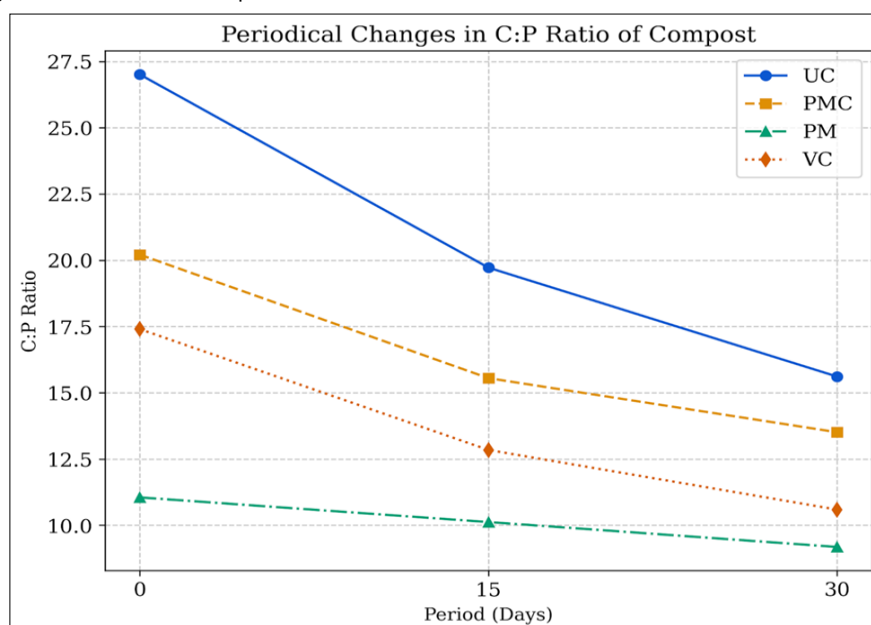


Fig. 3. Periodical changes in the C:P ratio of composts.

Relationship between C : N and C : P ratios

The correlation analysis between C : N and C : P ratios revealed a strong and significant positive relationship ($r = 0.830$, $R^2 = 0.689$, $p < 0.001$), indicating that nearly 69 % of the variation in C : P ratio is explained by changes in the C : N ratio (Fig. 4). The upward regression trend demonstrates that compost samples with higher C : N ratios also exhibited higher C : P ratios, reflecting synchronised reductions of C relative to N and P during decomposition. Among the compost types, UC and PMC generally recorded higher C : N and C : P ratios, whereas PM and VC showed comparatively lower values, indicating faster stabilisation and nutrient mineralisation.

Total organic carbon (%)

The TOC content during characterisation was highest in PMC (24.25 %), followed by PM (23.20 %), VC (19.14 %) and UC (18.91 %), indicating greater organic matter content in press mud compost and PM. During enrichment, TOC progressively decreased in all composts from 15 to 30 days, reflecting active microbial decomposition and carbon mineralisation Fig. 5. At 15 days, TOC ranged from 17.75 % (UC) to 23.32 % (PMC), which further declined by 30 days to 17.17 % (UC), 22.97 % (PMC), 21.11 % (PM) and 16.94 % (VC). The percentage carbon loss after 30 days was highest in VC (11.49 %), followed by UC (9.20 %) and PM (9.01 %), while PMC showed the lowest loss (5.28 %).

Discussion

The enhancement of nutrient content and microbial activity in enriched compost can be attributed to the functional roles of the inoculated microbial consortia. *Azotobacter chroococcum*, a free-living N-fixing bacterium, increased the N content of compost by converting atmospheric N into forms available for microbial and plant uptake. Phosphate-solubilising bacteria (*B. polymyxa*, *P. striata*) facilitated the solubilisation of insoluble phosphates, thereby increasing plant-available phosphorus, while KSB (*Bacillus* spp., *P. fluorescens*) enhanced the release of potassium from mineral sources. These microbes survived and proliferated within the compost environment, contributing to organic matter mineralisation, C/N cycling and overall microbial biomass enrichment.

Trichoderma spp. played a complementary role in compost stabilisation and biocontrol. Its enzymatic activity, including cellulase and chitinase production, promoted the degradation of complex organic matter, accelerating compost maturity. Additionally, *Trichoderma* suppressed the growth of potential pathogenic fungi, maintaining microbial balance and enhancing the safety and quality of the enriched compost. Collectively, the synergistic action of the bacterial consortium and *Trichoderma* spp. resulted in improved nutrient availability, microbial persistence and compost stability across all tested substrates.

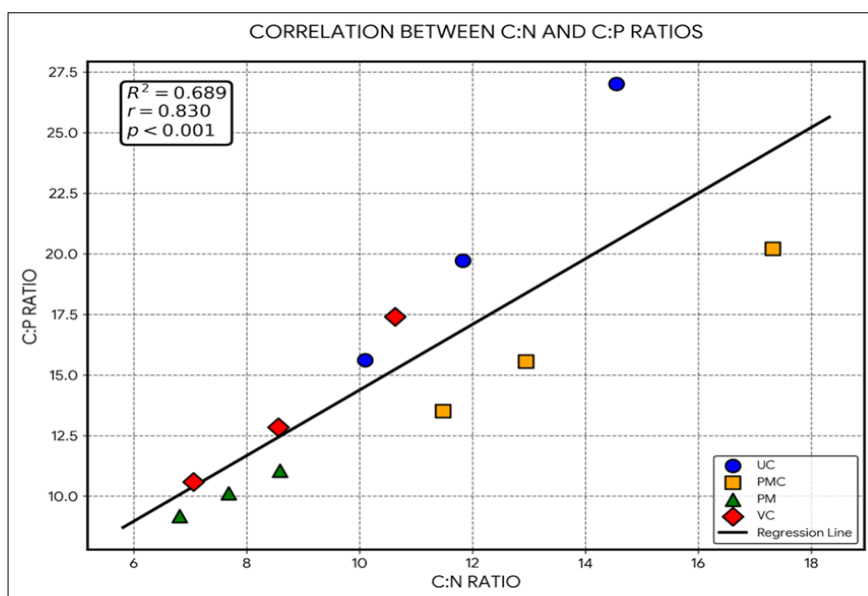


Fig. 4. Relationship between C : N and C : P ratios.

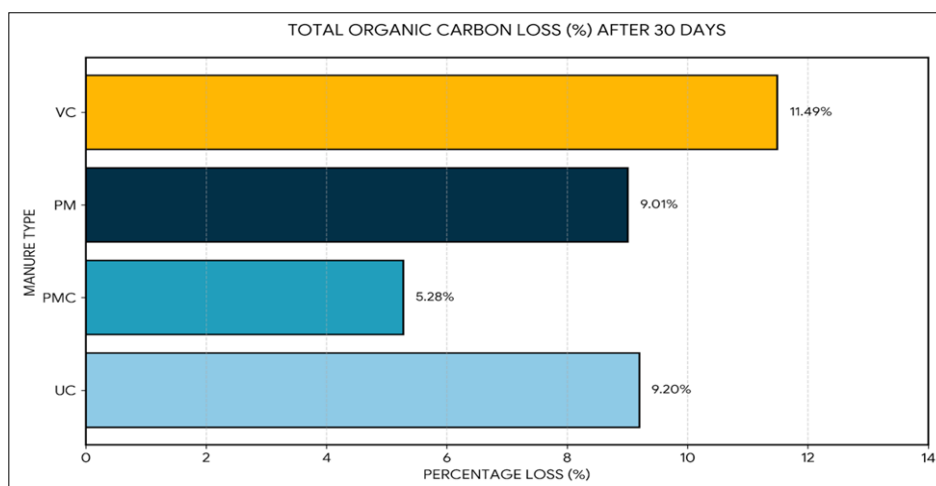


Fig. 5. Total organic carbon loss (%) after 30 days.

The considerable variation in physico-chemical, nutrient and biological properties among compost sources reflected differences in raw materials and decomposition status. The neutral to slightly alkaline pH is favourable for nutrient availability and microbial activity. The higher electrical conductivity in poultry manure may be attributed to higher soluble salt content. Greater organic matter accumulation in press mud compost and poultry manure indicates enhanced substrate availability. Lower C : N ratios in poultry manure and vermicompost suggest rapid mineralisation and indicate compost maturity, as C : N ratios below < 10–15 are generally considered a benchmark for well-stabilised compost whereas the higher ratio in FYM indicates slower nutrient release (22). The superior nutrient status of PM and VC highlights their potential as enriched organic inputs (1). Significantly higher microbial activity and biomass were observed in PM PMC than in UC following microbial inoculation, confirming the superior biological responsiveness of nutrient-rich substrates (23). Poultry manure performed best because it is rich in readily available (labile) C and nutrients, including simple carbohydrates, proteins and uric acid, which provide immediate energy for microorganisms, stimulating rapid microbial growth and enzymatic activity. Its low C:N ratio reduces N immobilisation and promotes faster mineralisation of N, P and K, accelerating decomposition and compost stabilisation. The higher initial microbial population in PM also enhances the effectiveness of the introduced microbial consortium, creating synergistic interactions that further improve organic matter

breakdown. In contrast, composts like press mud and UC contain more recalcitrant carbon (e.g., lignin and complex polysaccharides), which slows decomposition and limits microbial activity. Thus, the superior performance of PM is driven by its labile carbon content, balanced nutrients, low C : N ratio and high microbial activity, leading to faster nutrient mineralisation and improved overall compost quality presented in Fig. 6.

Consistent with earlier studies (24–28), microbial inoculation significantly enhanced nutrient availability, including plant-available P and N retention, while promoting microbial persistence and activity. It also accelerated C mineralisation and improved compost maturity and overall quality across nutrient-rich substrates such as PM, VC and PMC. The marked improvement in nutrient content and microbial population with composting duration indicates enhanced nutrient enrichment and mineralisation. The increase or stabilisation of micronutrients suggests improved nutrient availability during compost maturation. The significant rise in microbial populations reflects active decomposition and enhanced biological activity. Overall, the results indicate that enrichment and extended composting duration (30 days) significantly improved nutrient status and microbial dynamics, with PM and VC showing measurable indicators (low C : N, high microbial biomass) and maturity compared to UC and PMC.

The statistically significant increase in nutrient levels after enrichment indicates that microbial activity effectively enhanced

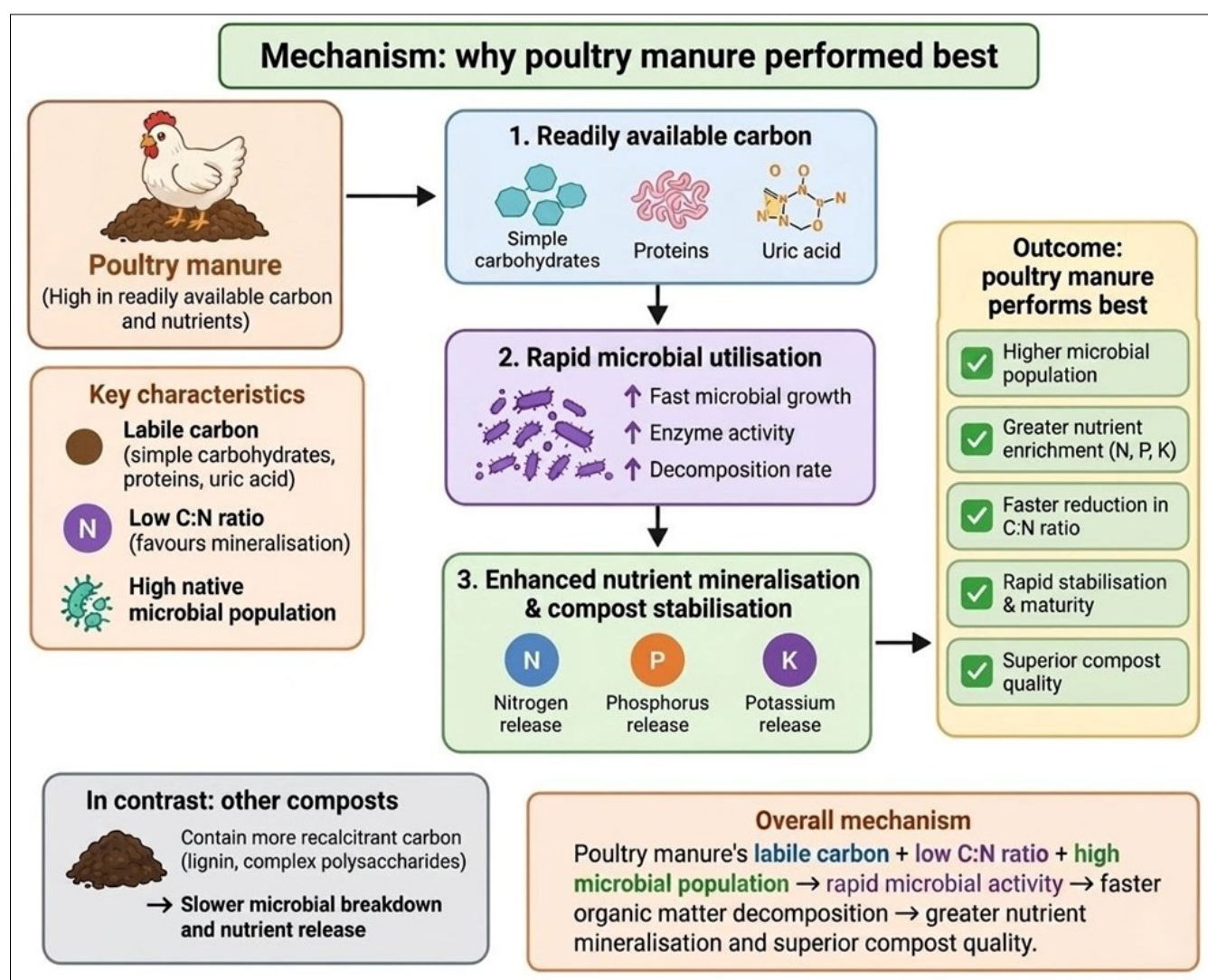


Fig. 6. Proposed mechanism underlying the superior performance of poultry manure.

compost quality within the enrichment period. The high Pearson correlation values indicate consistent trends among paired observations before and after microbial enrichment, reflecting similar directional changes in nutrient transformation across compost types. Overall these findings confirm that microbial inoculation accelerated nutrient mineralisation and improved the overall nutrient status of the compost. Nutrient content, particularly N, P and K, increases with microbial enrichment, as reported in PM, VC and UC (24, 29–31). Additionally, microbial populations, enzyme activities, humic acid content and germination index are improved, reflecting enhanced biological activity and overall compost quality (23, 28, 32, 33). Overall, microbial enrichment produces nutrient-rich, biologically active and mature compost suitable for sustainable agriculture.

Microbial inoculation of PM accelerated composting to 30 days, reduced the C : N ratio and improved N retention, indicating rapid stabilisation and enhanced compost quality (34). Inoculation with cellulolytic and ligninolytic bacteria accelerated composting, lowered the C : N ratio, increased humic acid content and improved seed germination, indicating enhanced compost maturity and quality (32). Microbial inoculation with additives accelerated cow manure composting, reduced the C : N ratio, improved nutrient content and enhanced compost maturity and quality (35). It serves as an important indicator of compost maturity and decomposition rate. A lower C : N ratio reflects rapid microbial decomposition, enhanced nitrogen mineralisation and greater nutrient availability. Conversely, a higher C : N ratio indicates slower organic matter breakdown and temporary nitrogen immobilisation. During compost enrichment, a gradual reduction in the C : N ratio signifies active microbial activity and stabilisation of organic matter.

The microbial activity during composting likely accelerated carbon mineralisation and improved nutrient availability, as reported in earlier studies (32, 34, 35). Overall, the decreasing C : P ratio across all treatments reflects enhanced compost maturity and quality, with PM and VC reaching stable nutrient balanced compost faster than UC and PMC. These findings highlight the effectiveness of composting in nutrient retention and stabilisation, which is critical for producing high-quality organic amendments for soil fertility improvement. C:P ratio indicates the balance between C and P during composting and helps assess nutrient stabilisation. A decreasing C : P ratio during enrichment reflects progressive carbon mineralisation and relative enrichment or stabilisation of phosphorus. Lower C : P ratios are generally associated with improved compost maturity and better nutrient availability for plants.

The strong positive association suggests that as compost matures and carbon is mineralised, both C : N and C : P ratios decline simultaneously, serving as reliable indicators of compost maturity and quality. Overall, the results confirm that C : N and C : P ratios are closely linked and can be effectively used to assess the degree of compost stabilisation and nutrient balance.

Although VC recorded maximum carbon reduction, PM maintained substantial C mineralisation along with better nutrient enrichment and microbial activity (as observed earlier), indicating efficient stabilisation and superior compost quality. The continuous decline in TOC confirms progressive maturity of compost, with PM emerging as the most balanced and effective treatment.

Conclusion

Microbial enrichment significantly improved the nutrient content, microbial population and maturity of all composts within 30 days. Decreases in the carbon to nitrogen (C : N) ratio, C : P ratio and total organic carbon (TOC) indicated accelerated decomposition and stabilisation, while increases in nitrogen (N), phosphorous (P), potassium (K) and beneficial microbes indicated enhanced nutrient availability. Among the composts, poultry manure (PM) performed best, followed by vermicompost (VC), demonstrating greater nutrient enrichment and biological activity. In conclusion, microbial enrichment represents an effective strategy for producing high-quality, nutrient-rich compost for sustainable agriculture.

Future research directions:

- Investigate the long-term effects of microbially enriched compost on soil fertility, crop yield and soil microbial diversity under field conditions.
- Examine the interaction between enriched compost and various soil types or cropping systems to optimise application strategies.
- Assess the environmental impacts, such as greenhouse gas emissions or heavy metal immobilisation, associated with the use of enriched compost.
- Utilise molecular tools (e.g., metagenomics, qPCR) to identify key microbial taxa driving nutrient mineralisation and compost stabilisation.

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Authors' contributions

NBG designed the experiment, conducted laboratory analyses and prepared the manuscript. RST and MRP assisted in data analysis and statistical interpretation and participated in the experimental design and coordination. VSP and SRS supervised the research work. BMK contributed to methodology development and technical guidance. SGA and MMJ assisted in laboratory work and reviewed the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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During the preparation of this work, the authors used ChatGPT to improve language and clarity. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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